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Thermal neutron self-shielding factor in foils: a universal curve

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Abstract. The presence of a sample in the neutron field of a nuclear reactor creates a perturbation of the local neutron fluxes. In general, the interpretation of the sample activation due to thermal and epithermal neutrons requires the knowledge of two parameters: the thermal neutron self-shielding factor, G_{th}, and the resonance neutron self-shielding factor, G_{res}. In recent works, the authors established an universal curve of G_{res} for isolated resonances and various geometries. The present paper deals with the description of G_{th} in foils by means of an universal curve on the basis of a dimensionless variable which includes the physical, nuclear and geometrical properties of the sample. The universal curve is in very good agreement with experimental and calculated values obtained from the literature.The study of other geometries (spheres, wires and cylinders) is in progress.

1. Introduction

As is well-known, the irradiation of a sample in the neutron field of a nuclear reactor is affected by the local perturbation of the neutron fluxes produced by the sample [1].

In general, the interpretation of the sample activation due to thermal and epithermal neutrons requires the knowledge of two parameters: the thermal neutron self-shielding factor, G_{th}, and the resonance neutron self-shielding factor, G_{res}.

In recent works [2-4], the authors established an universal curve of G_{res} for isolated resonances or groups of isolated resonances, and various geometries of the samples (foils, wires, spheres, and cylinders).

In relation to G_{th}, some experimental [5-13] and theoretical studies [14] have been carried out to determine this factor for foils and wires of different elements. Their results are presented as tables or graphics of G_{th} for a given element and geometry as a function of the typical dimension. Recently, Copley [15] studied the scattering effect within an absorbing sphere and, according to his results, the self-shielding factor is obtained through a set of curves as a function of the macroscopic absorption and scattering cross-sections of the sample.

The present paper deals with the description of the thermal neutron self-shielding factor in foils by means of an universal curve. The study of other geometries (spheres, wires and cylinders) is in progress.

2. Calculation

For a given element, geometry and sample dimension, G_{th} is calculated as the ratio between the reaction rates per atom in the real sample and in a similar and infinitely diluted sample:

$$G_{th}(x)=\frac{\int_{E_1}^{E_2} M(E)\,\sigma_a(E)\,dE}{\int_{E_1}^{E_2} M_0(E)\,\sigma_a(E)\,dE} \tag{1}$$

where *x* is the typical sample dimension, $M_0(E)$ is the non-perturbed thermal (maxwellian) neutron flux per unit energy interval (inside the infinitely diluted sample), $M(E)$ is the perturbed thermal neutron flux inside the real sample, $\sigma_a(E)$ designates the (n,γ) cross-section, and E_1 and E_2 are, respectively, the lower and the upper limits of the thermal neutron spectrum at room temperature. The total neutron cross-section is adopted in the calculation of the perturbed neutron flux, thus taking into account the neutron scattering in the sample. In the calculations, the density for infinite dilution is assumed to be $\rho = 10^{-6}\rho_0$, ρ_0 representing the density of the real sample.

Thermal neutron self-shielding factor in foils of very different elements (see Table 1) have been calculated using the MCNP code [16].

TABLE 1. *Physical and nuclear properties of the studied elements* [17, 18]

Element	A (g mol^{-1})	ρ (g cm^{-3})	σ_t (b)	σ_s (b)	σ_a (b)
Al	26.98	2.7	1.617	1.414	0.203
Au	196.97	19.3	95.05	6.86	88.19
Cd	112.41	8.65	2996.5	11.54	2985.0
Co	58.93	8.9	38.98	6.02	32.96
Cu	63.55	8.96	11.23	7.87	3.36
Eu	151.96	5.24	3655.6	6.61	3649.0
Gd	157.25	7.9	36892.3	138.7	36753.6
In	114.82	7.31	176.8	2.55	174.3
Ir	192.22	22.42	384.2	14.7	369.5
Mo	95.94	10.22	7.77	5.48	2.29
Ni	58.69	8.9	22.58	18.69	3.89
Pb	207.20	11.35	11.22	11.07	0.15
Pt	195.08	21.45	21.5	12.4	9.1
Rh	102.91	12.41	136.2	3.25	132.9
Sc	44.96	2.99	46.54	22.48	24.06
Sm	150.36	7.52	8419.3	52.3	8367.0
Ta	180.95	16.65	24.02	5.64	18.38
Fe	55.85	7.86	13.93	11.48	2.45

$\sigma_t, \sigma_s, \sigma_a$ are, respectively, the total, scattering and absorption microscopic cross-sections averaged over the thermal neutron spectrum at room temperature [17].

In order to eliminate practically the effect of the neutrons entering through the foil edge, a ratio of $R/t \geq 100$ (with $R \geq 1$ cm) has been adopted, *t* and *R* being the thickness and the radius of the foil, respectively.

3. Results and discussion

As is shown in Figure 1, the value of G_{th} depends on the physical and nuclear properties of the material as well as on the foil thickness.

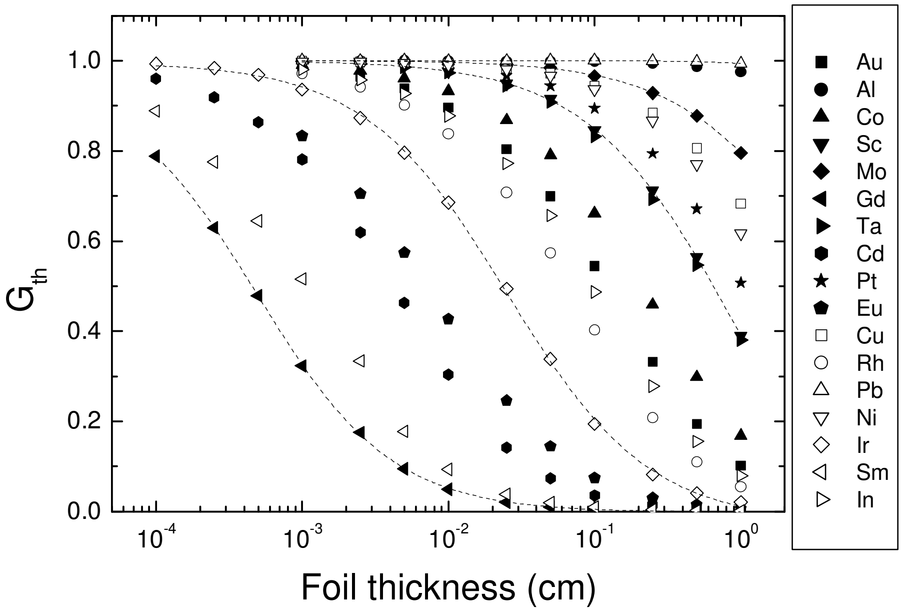

Figure 1. *Calculated G_{th} as a function of the foil thickness*

However, it is possible to introduce a dimensionless variable, z, which converts that dependence into an unique curve. The analysis of the results obtained in the foil (or slab) geometry has shown that this variable is given by:

$$z = t\,\Sigma_t \left(1 - \frac{\Sigma_s}{\Sigma_t}\right)^{0.85} = t\,\Sigma_t \left(\frac{\Sigma_a}{\Sigma_t}\right)^{0.85} \qquad (2)$$

where Σ_t, Σ_s and Σ_a are, respectively, the total, scattering and absorption macroscopic cross-sections averaged over the thermal neutron spectrum, and t is the thickness of the foil. Note that the variable z takes into account the neutron scattering in the sample.
The analysis of the results also shows that a sigmoid is the best curve to be fitted to the calculated $G_{th}(z)$ values. The expression of this curve is

$$G_{th}(z) = \frac{A_1 - A_2}{1 + \left(\frac{z}{z_0}\right)^p} + A_2 \qquad (3)$$

where A_1, A_2, z_0 and p are the curve parameters, to be adjusted to the calculated values. Note that A_1 is the limit of G_{th} as z tends to zero; A_2 is the limit of G_{th} as z tends to infinity; z_0 is the inflexion point [$G_{th}(z_0) = (A_1+A_2)/2$]; and p is related with the gradient of the curve at $z = z_0$.

Figure 2 shows the calculated values of $G_{th}(z)$ and the sigmoid (universal curve) adjusted to all the points. The values of the curve parameters are:

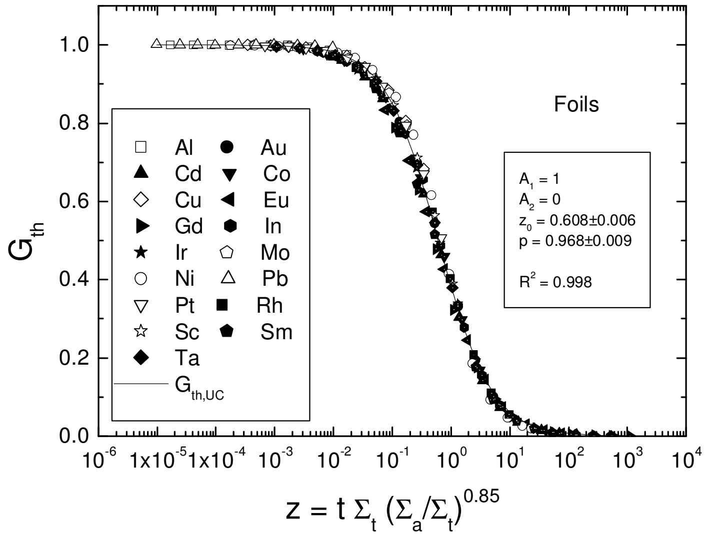

Figure 2. *Calculated G_{th} and the universal curve ($G_{\mathrm{th,UC}}$)*

$$A_1 = 1; \quad A_2 = 0; \quad z_0 = 0.608 \pm 0.006; \quad p = 0.968 \pm 0.009 \tag{4}$$

For more than 90% of the results, the relative deviation between the universal curve and the calculated values is less than 4% for $z<1$ (z domain of practical interest).

In Figure 3, the universal curve is compared with experimental and calculated values of G_{th} from the literature. As can be observed, the overall agreement is very good, thus confirming the validity of the relations (2) to (4) to determine the thermal neutron self-shielding factor in foils. The maximum relative deviation between the universal curve and the experimental values is less than 5%.

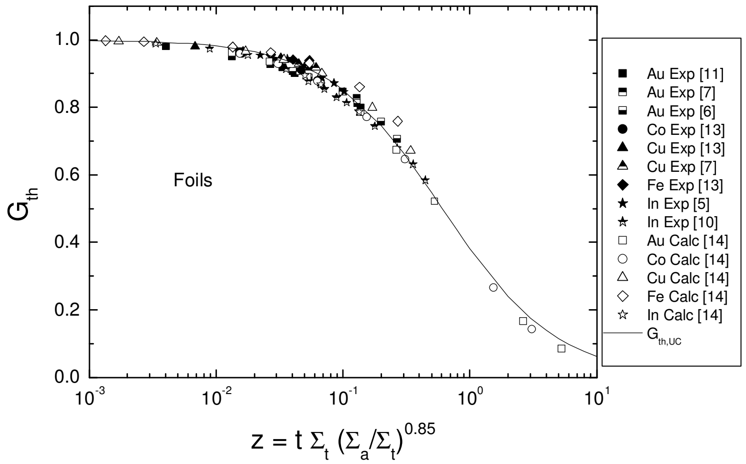

Figure 3. – *Comparison of the universal curve ($G_{\mathrm{th,UC}}$) with experimental and calculated values from the literature*

4. Conclusion

In spite of large differences between the physical and nuclear properties of the studied elements, an universal curve can describe the behaviour of the thermal neutron self-shielding factor for foil samples. In this curve, G_{th} is expressed as a function of a dimensionless variable, which takes into account the physical and nuclear properties of the sample. The universal curve is in very good agreement with experimental and calculated values obtained from the literature. The maximum relative deviation between the universal curve and the experimental values is less than 5%.

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